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A TECHNOLOGY ROADMAP FOR ESTABLISHING AN INTERPLANETARY INTERNET

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Abstract

NASA's future mission set calls for significant increases in deep space communications capabilities. Activities such as the intensive exploration of Mars will benefit from and be enabled by breakthrough increases in bandwidth and connectivity. A solar system-wide information architecture, modeled on the Earth's Internet, is envisioned in which information can seamlessly flow from planetary environments back to scientists and the public here on Earth. Significant increases in deep space communications bandwidth will be required to achieve NASA's goal of creating a virtual presence throughout the solar system. We present here an overview of some of the key technologies that will play a role in realizing this vision.

Introduction

NASA's strategic plan calls for establishing a virtual presence throughout the solar system. The fidelity of that virtual presence will largely be defined by our capability to move large amounts of information across interplanetary distances. Relative to that goal, today's current deep space communications capabilities represent a severe limitation in planetary exploration. Over the past year, the Telecommunications and Mission Operations Directorate (TMOD) at the Jet Propulsion Laboratory (JPL) has developed a technology roadmap that presents a path to significant growth in NASA's communications bandwidth across the solar system. This paper presents a summary of that roadmap, and describes how it supports the notion of an Interplanetary Internet.

The Internet provides a model for how to embed this communications growth in an evolving architecture that supports information flow across the solar system. While past deep space missions traditionally represented single point-to-point links between a planetary spacecraft and Earth, the future calls for more complex network topologies, with *in situ* exploration involving landers and rovers communicating through networks of relay satellites. We envision an Interplanetary Internet that extends the paradigm of the Earth's Internet to the solar system. Key aspects of this Interplanetary Internet include:

- breakthrough increases in communications bandwidth and connectivity
- IP-like protocols, tailored to operate over the long round-trip light times of interplanetary links
- a layered architecture to support evolvability and interoperability
- seamless end-to-end information flow between science and exploration assets around the solar system and researchers and the public here on Earth

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- integration of navigation functionality to extract position information from the communications links.

Key Technologies

Ka-band Ground Systems

Because the achievable data rate for a telecommunications system scales inversely with the square of the communications distance, data return from deep space missions is fundamentally constrained by the challenges of communicating over planetary distances. To put this in perspective, the distance from Earth to Mars is up to 10,000 times the distance from the surface of the Earth to a geostationary satellite. This increased distance means that the space loss for the deep space link is 100,000,000 times, or 80 dB, larger than for the geostationary link. The large apertures and highly sensitive receivers of NASA's Deep Space Network are driven by the need to compensate for these enormous space losses. Nonetheless, deep space communications rates are typically orders of magnitude lower than data rates we take for granted over the Earth's terrestrial Internet. Central to developing a true Interplanetary Internet must be targeted technology developments aimed at increasing the achievable data rates over deep space links.

Today's deep space missions typically communicate at an X-band frequency of 8.4 GHz. As a first step in significantly increasing the available deep space communications capability of its Deep Space Network, NASA is initiating the implementation of Ka-band (32 GHz) reception capabilities on all of its ground assets [1]. For a given size spacecraft antenna, moving to a higher communications frequency allows the spacecraft to focus its transmitted signal into a narrower beamwidth, thereby increasing the received flux of the signal at Earth and hence increasing the data rate that can be supported for a given transmitted power.

While the move from X-band to Ka-band would naively lead to a performance increase of $(32/8.4)^2$, or roughly a factor of 14.5, the increased effects of the atmosphere at Ka-band, and the lower efficiency of key transmit and receive components reduce this performance advantage. Nonetheless, even accounting for all of these effects, it is expected that the transition to Ka-band will offer roughly a fourfold, or 6 dB, increase in deep space communications capability.

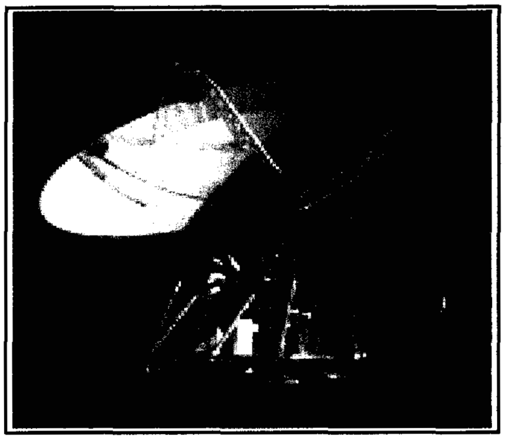

Figure 1: DSS 13, the DSN's 34m Research and Development Antenna

Enabling the DSN's antennas to perform well at 32 GHz, with the much shorter 0.9-cm Ka-band wavelength, poses significant challenges in terms of aperture efficiency and antenna pointing. As these large antennas tip in elevation, the time-varying effects of gravity can lead to significant distortions or the primary antenna surface relative to the scale of the Ka-band wavelength. The DSN's new 34m beam waveguide (BWG) antennas (Figure 1) were designed with very stiff backup structures specifically to minimize these deformations, with Ka-band applications in mind; these new antennas provide excellent aperture efficiency of better than 50% over the full range of elevations angles.

The DSN's older 70m antennas, however, suffer much larger gravity-induced deformations. If left uncorrected, these deformations would preclude the use of the 70m subnet for Ka-band reception. JPL is investigating two approaches to compensating for these deformations and achieving good Ka-band aperture efficiency on these large antennas (Figure 2). In the first of these, a deformable flat plate mirror, instrumented with 21 actuators, is placed in front of the 70m Ka-band feed [2]. Based on holographic measurements of the primary 70m antenna's deformation as a function of elevation angle, the actuators are programmed to deform the deformable mirror to exactly compensate for those deformations.

A second approach achieves this wavefront compensation in the electronic, rather than the mechanical, domain. In this approach, a seven-element Ka-band array feed, with a central feed surrounded by a ring of six outer feeds, is used to collect the defocused and wavefront-distorted signal resulting from the primary antenna surface deformations [3]. By cross-correlating the received signal in each pair of array feed elements, the relative phase and amplitude of the signal can be determined for each feed element. These in turn yield a set of complex weights which are used to optimally recombine the seven feed signals into a phase-compensated signal. Both of these systems have been installed this year on the Goldstone 70m DSN antenna with the goal of quantifying to potential Ka-band performance of these large apertures and establishing a recommended implementation approach.

The shorter Ka-band wavelength also increases the challenge of pointing these large antennas, since the antenna beamwidth is proportional to the RF communications wavelength divided by the antenna diameter. At Ka-band, the beamwidth of a 34m antenna is only 15 mdeg, four times smaller than at X-band. On the 70m antennas, the beamwidth is an even smaller 7 mdeg.

Again, two candidate approaches are being developed to support accurate Ka-band pointing. First, a new feed is being developed which combines X-band transmit and receive capabilities with a Ka-band tracking feed, all in a single feed package. This system will be capable of providing closed-loop pointing to Ka-band signals with an accuracy of better than a millidegree [4]. This feed can be used by itself to provide precise pointing for 34m DSN antennas, and can be combined with the deformable flat plate on the 70m to provide a comprehensive gravity compensation and pointing system. Alternatively, the Ka-band array feed system itself intrinsically supports precision pointing as it provides a direct measure of the spatial distribution of the received beam across its seven feed elements.

Because the figure of merit of the DSN antenans is the ratio of effective aperture to receive system noise temperature, another critical Ka-band ground system technology is cryogenic low-noise amplifiers. Recent efforts have focused on reducing the noise temperature of Indium Phosphide (InP) High Electron Mobility Transistor (HEMT) devices. JPL has teamed with TRW and the Georgia Institute of Technology to develop low noise amplifiers with module noise temperatures as low as 10 K. Even lower noise temperatures can be achieved with maser-based amplifier systems [5].

Based on these technologies, the DSN is working towards the implementation of a Ka-band receive capability on all of its 34m beam waveguide antennas by 2004, with an aperture efficiency of 53% and a system noise temperature of 71 K, at 30 deg elevation and 90% weather. In subsequent years, Ka-band would be added to the 70m antennas, using either the deformable mirror or the array feed, or a combination of both, depending on the outcome of this year's tests. Current goals for the 70m are an aperture efficiency of 36% and a system noise temperature of 71 K.

Spacecraft Radio Systems

The transition to Ka-band requires parallel development of Ka-band flight components. Key elements of the spacecraft radio system include transponders, power amplifiers, and antennas. For deep space missions, key drivers on these systems are minimizing mass, volume, and power while maximizing EIRP, all while reducing system cost.

The Small Deep Space Transponder (SDST) represents the first commercial Ka-band deep space radio. The SDST supports an X-band uplink and X- and Ka-band downlinks, and has been successfully validated in its first flight, on

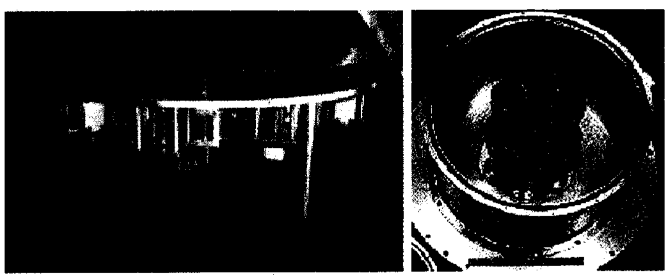

Figure 2: Deformable mirror (left) and seven-element array feed (right), two candidate technologies for achieving high aperture efficiency at 32 GHz on the DSN's 70m antennas.

the New Millennium DS1 mission. JPL is currently developing a next-generation deep space transponder, called the Spacecraft Transponding Modem (STM), with the goal of achieving significant reductions in mass, volume, power, and recurring cost relative to SDST, while introducing new performance-enhancing capabilities [6]. With a projected mass of under 1 kg and a DC power requirement of only 11 W, the STM will also for the first time support new classes of error correcting codes known as turbo codes, provide simple frame-level interfaces with the spacecraft flight computer, provide precision frequency and timing references for the rest of the spacecraft, and support fast carrier acquisition, eliminating the need for sweeping the uplink carrier. A full prototype of the STM is currently under development, with completion targeted for 2000.

A significant current obstacle to the use of Ka-band is the low output power and efficiency of current solid state power amplifiers (SSPAs). For example, the Ka-band SSPA on the New Millennium DS1 mission provides about 2.5 W of RF power with only about 15% efficiency. In the long term, device improvements coupled with quasi-optic power combining techniques should lead to highly efficient power amplifiers with scalable output power, but in the near term, traveling wave tube amplifiers (TWTAs) appear to be the fastest path to Ka-band spacecraft amplifiers with the desired characteristics. A prototype Ka-band TWTA is being developed with goals of 15-30 W output power, better than 40% efficiency, and less than 2 kg mass.

Spacecraft antennas represent a third area of Ka-band flight technology. The Mars Global Surveyor (MGS) spacecraft is currently flying a 1.5-meter X/Ka-band Cassegrain high-gain antenna as part of the MGS Ka-band Link Experiment [7], achieving a gain of 49.0 dBi at 32 GHz. This antenna provides a simple solution for fixed antennas that can fit within the volume constraints of today's smaller launch vehicles. We are also exploring several other novel spacecraft antenna technologies. Several years ago, a 0.5-meter Ka-band reflectarray antenna was built at JPL [8]. In this antenna, a flat surface is covered with passive phase shifting elements, designed so that when illuminated by a Ka-band primary feed, the flat surface behaves like a parabola. More recently, the reflectarray technique is being combined with inflatable structure technologies to build larger apertures with very low areal density [9]. The combination of inflatables with reflectarrays is particularly attractive as the reflectarray elements can be placed on a thin, flat sheet which simply needs to be stretched taut by an inflatable torus around its circumference. Using this approach, a 3-meter Ka-band reflectarray antenna is being developed at JPL.

Optical Communications

Atmospheric effects limit the potential of RF space-to-ground communications above 32 GHz. For further increases in deep space link performance, JPL is exploring the potential of laser-based optical communications. The extremely short wavelength of optical frequencies leads to much higher directivity of the transmitted spacecraft signal. Whereas a diffraction-limited 2-meter Ka-band antenna transmits with a beamwidth of about 5 millirad, a 1064 nanometer optical signal transmitted through a 30-cm diffraction-limited telescope has a beamwidth of only 3.5 microradians. The narrower beam offers the potential for high-rate deep space communications from small, low-power optical transceivers, but introduces new challenges in terms of spatial beam acquisition and tracking.

Important steps have already been taken in the development of space optical communications capability. From November, 1995 to May, 1996, JPL and Japan's Communications Research Laboratory conducted the first bi-directional space-ground optical communications using NASDA's ETS-VI spacecraft and existing telescopes at JPL's Table Mountain Facility (Figure 3) [10,11].

Currently, JPL is developing small, lightweight spacecraft optical transceivers for use in future missions [12,13]. The Optical Communications Demonstrator (OCD) represents a prototype transceiver applicable to deep space or high-rate earth orbit applications. Incorporating a simple architecture which uses a single fine steering mirror and a single detector array for acquisition and tracking of an uplink laser beacon, and for vernier pointing of the downlink beam.

To support future near-term demonstrations of space-to-ground optical communications from low-Earth orbit, TMOD has recently initiated the development of a 1-meter Optical Communications Telescope Laboratory (OCTL) at JPL's Table Mountain Facility in southern California. The OCTL ground station will be used to during the planned ISSERT demonstration on the International Space Station, scheduled for 2002. OCTL will also provide an R&D testbed for developing the ground system technologies that would ultimately be used for deep space optical communication applications.

Operational deep space optical communications will require larger ground apertures. Ten-meter class "photon buckets", with relatively low-cost, non-diffraction-limited surfaces, would be used to provide adequate receive sensitivity. Uplink signals, for telecommand and/or to serve as a beacon pointing reference for the spacecraft, would be transmitted by an OCTL-class 1-meter telescope, augmented with adaptive optics to reduce the effects of the atmosphere on the uplink pointing direction and beamwidth.

Based on current optical communications system design, a single 10m ground station supporting a downlink from a spacecraft at Jupiter equipped with a 3W, 30 cm optical transmitter could achieve roughly the same data rate as the equivalent performance of *all* of the DSN's current X-band antennas arrayed together, receiving a 10W X-band signal from a 1.5-meter spacecraft antenna. And it is expected that future component level improvements in optical detector and laser efficiencies, as well as improved optical modulation and coding schemes, will further increase these performance gains. NASA's current communications roadmap calls for technology development and demonstrations in the 2000-2005 time frame with OCTL, and the initial deployment of the first operational 10m ground station(s) in the 2008-2010 time frame. Looking beyond 2010, an important strategic decision is whether to continue the relatively low-cost development of optical ground stations, which must contend with significant atmospheric effects, or to move to Earth-orbiting assets to support deep space optical communications. Technology breakthroughs in low-cost spacecraft and lightweight optical system will play a key role in this decision.

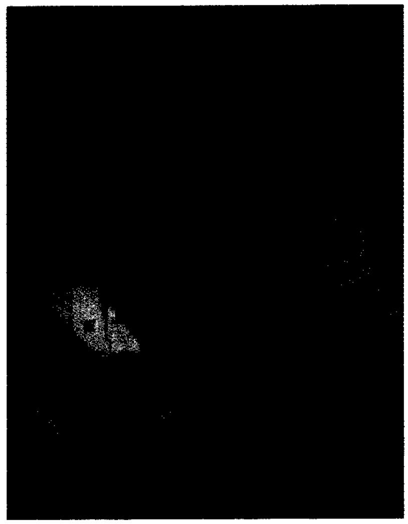

Figure 3: Multi-beam laser uplink from Table Mountain 0.6m Telescope to the ETS-VI spacecraft during the Ground to Orbit Lasercom Demo (GOLD)

In Situ Communications and Navigation

Small planetary landers and rovers will demand highly efficient, low-mass, low-power short-range communications. Constellation and formation flying applications, such as future space interferometer missions with distributed free-flying apertures, are another scenario where short-range communications solutions are required. In many of these cases, missions will benefit from also extracting accurate radio metric observables from these in situ links to achieve precise navigation for high-accuracy landing, rendezvous and docking, and/or precision constellation control.

Several parallel thrusts are underway at JPL in response to these needs. The Micro Communications and Avionics System (MCAS) targets a highly integrated short-range radio incorporating a mixed signal ASICs and MEMS-based oscillators and filters to achieve aggressive mass, power, and volume goals [14]. A second approach, dubbed the Autonomous Formation

Flyer, exploits GPS-on-a-chip technology to develop a flexible microprocessor-based chipset that combines precise one-way carrier phase and pseudorange measurements with high-rate telemetry [15]. Each of these approaches are well-suited to specific classes of mission needs.

Protocols, Coding and Data Compression

The layered architecture of the Internet Protocols (IP) stack provides reliable file transfer (FTP) atop the TCP/IP transport protocol. However, deep space links involve characteristics that preclude the use of the current Internet Protocol (IP) standards, which were designed for use on low bit-error-rate, fiber-based terrestrial links. By contrast, deep space links involve very long round trip light times, low signals-to-noise ratios and relatively higher bit error rates, and intermittent link availability. In order to provide the higher-level communications functionality of the current IP stack, JPL is developing new deep space communication protocols tuned to the deep space environment. The CCSDS File Delivery Protocol (CFDP), currently in development, will provide for reliable and robust file delivery from in situ vehicles back to Earth, even through multiple, intermittent relay communications links [16].

Error correcting codes are used to increase the achievable data rate on power-constrained deep space links. A new class of codes, known as turbo codes, is being developed to provide enhanced performance [17]. These codes offer more than 2 dB of improvement relative to a standard (7,1/2) convolutional code, and nearly 1 dB better that the DSN's current state-of-the art (15,1/6) code. Another important aspect of turbo codes is the relatively low complexity of their decoding algorithms. This reduced complexity will allow the use of turbo codes at higher data rate, and should lead to lower cost decoder systems. TMOD is currently developing a prototype DSP-based turbo decoder; implementation of an operational turbo decoding capability within the DSN is planned by 2003.

While the technologies discussed above will all contribute towards increasing the achievable data rates on deep space links, these rates will typically still lag far behind terrestrial and near-Earth capabilities. As a result, data compression and onboard processing techniques will be critical in maximizing the information that can be conveyed over interplanetary links. New wavelet-based compression schemes are being developed for the Mars Surveyor Program and other deep space applications with high compression ratios at reduced distortion. Extending these concepts, onboard processing of science data will be used to identify highest-value data sets for transmission to Earth.

A Mars Network for Telecommunications and Navigation

The coming decade will see an intensive, multi-agency program of orbital and surface exploration at Mars. NASA's Mars Surveyor Program is planning a series of sample return missions, starting in 2003, in which sophisticated landers and rovers will be employed to select prioritized samples, which will be placed in Mars orbit by a Mars Ascent Vehicle. There, they will rendezvous with a CNES-supplied sample return orbiter, which will collect the sample canister and return it to Earth. In this same time period, CNES will be deploying a network of landers, collecting meteorological and seismic data from four surface locations, and ESA will be operating a science orbiter and a British supplied lander. Longer-term plans include "robotic outposts" – surface sites in which multiple robotic vehicles would establish a sustained presence on the Martian surface – and, ultimately, piloted missions.

This intensive program of exploration calls for a dedicated communications and navigation infrastructure to enhance data return and enable new classes of in situ spacecraft. The recent Mars Pathfinder mission quantifies the needs. The Pathfinder lander utilized a direct-to-Earth communications radio system with a mass of 10 kg and DC power of 68 W. The high power demand limited operation of this system to just a few hours per sol. (A "sol" is one Martian day, roughly 25 hrs in duration.) Average data return over the life of the lander was only 30 Mb/sol. By contrast, a single, full-resolution stereo panorama constitutes a data volume of 500 Mb. This telecommunications bottleneck significantly limited the amount of surface imagery that could be returned, and the limited connectivity dictated a slow, once-per-sol planning cycle.

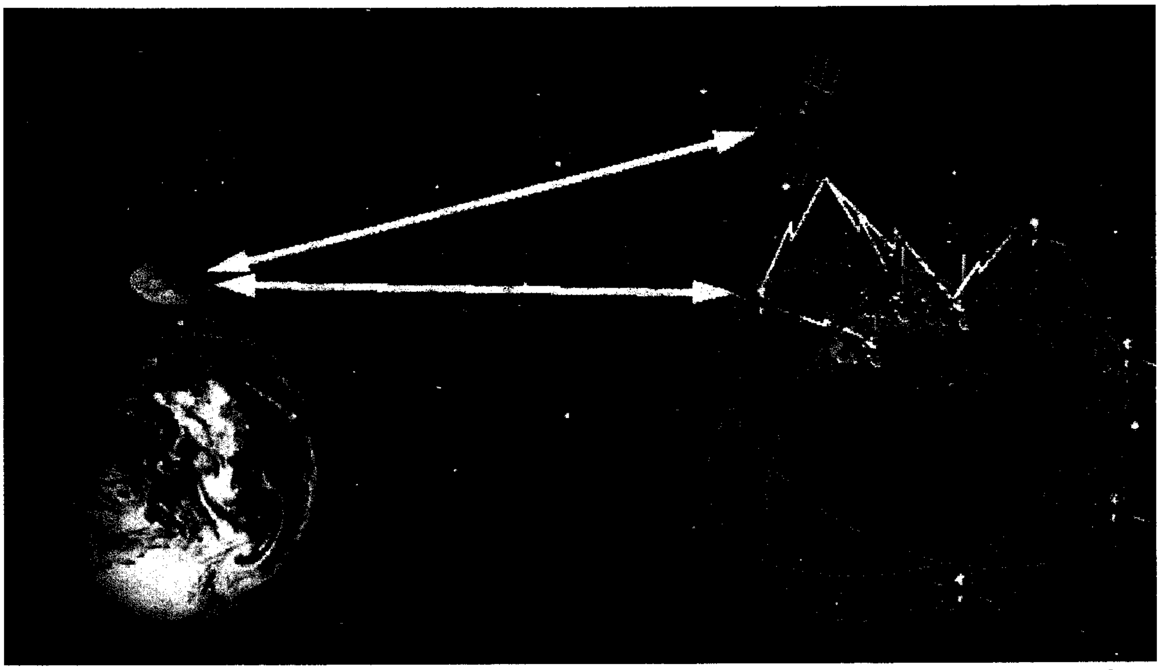

Figure 4: Conceptual view of a Mars Network for providing enhanced and enabling telecommunications and navigation capability for future robotic and human mission to Mars.

Future exploration will demand greatly increased data return and connectivity. Long-range rovers will be providing frequent panoramas to support sample selection and route planning. Complex surface operations will require multiple contacts per sol. Other mass- and power-constrained classes of surface explorers, such as microlanders and microprobes, will not be able to support direct-to-Earth links; these classes of missions will be enabled by sensitive relay communications orbiters.

With this in mind, TMOD is carrying out a Phase A study of a Mars Network – a constellation of orbiting satellites at Mars providing enhancing and enabling telecommunications and navigation services to future Mars missions. Figure 4 depicts a conceptual view of the Mars Network, built around two basic building blocks. The first building block of this network, is a low-cost microsatellite which can be launched as a piggyback payload on an Ariane V commercial launch. With a total mass of only 220 kg, the microsatellite carries a 400 MHz UHF radio system for communications with Mars surface assets, and an X- or Ka-band radio system for communications with Earth. Current plans call

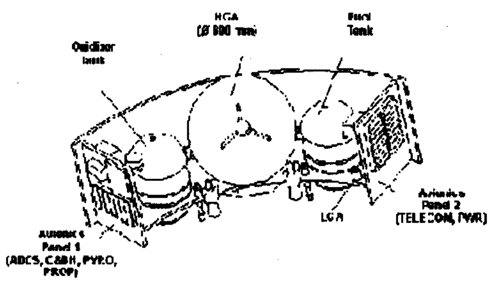

Figure 5: Mars Network Microsatellite

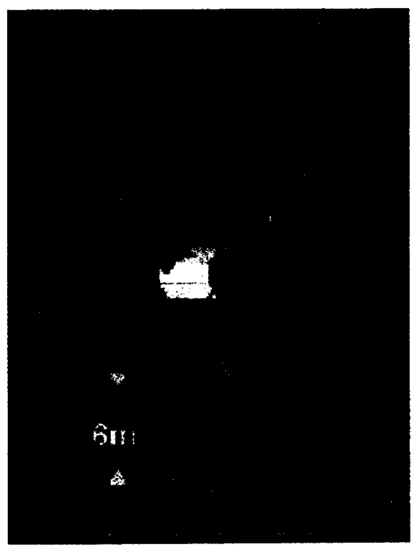

Figure 6: Mars Areostationary Relay Satellite (MARSAT)

for developing a constellation of six of these microsatellites orbiting at an altitude of 800 km: two in near-equatorial orbits and four in inclined 111 deg orbits. This configuration provides frequent contact and high data volume return from the low-latitude sites targeted for sample return missions, while also ensuring good global coverage. The tight mass and volume constraints of the piggyback launch mode will drive a largely single-string design for these microsatellites; redundancy will be at the constellation level, based on multiple satellites. A conceptual design for this microsatellite is shown in Figure 5.

The second building block of the Mars Network is the Mars Areostationary Relay Satellite, or MARSAT, depicted in Figure 6. MARSAT is motivated by the desire to support continuous streaming video from the surface of Mars back to Earth. MARSAT flies in the Mars equivalent of a geostationary orbit; in an equatorial, 17,000-km altitude circular orbit with a period of one sol, it will have a continuous view of one side of the planet. From this vantage point, MARSAT will utilize a directional X-band link to receive a 1 Mb/s data stream from the surface and then transmit this to Earth via a high-EIRP Ka-band link. Surface users will require only a small payload to support this 1 Mb/s data rate. One concept for a MARSAT-compatible surface user terminal would radiate 2 W at X-band through a small, 20 cm directional antenna. With a relatively broad beamwidth of 10 deg, the pointing requirements on the surface should be quite manageable, given that MARSAT will remain at a fixed point on the sky as viewed from the surface.

NASA is currently examining options for deploying a Mars Network based on a combination of these building blocks. Figure 7 summarizes how our ability to return data from Mars could increase with the implementation of a Mars Network over the coming decade, under the assumption that the first microsatellite is deployed in the 2002/2003 Mars opportunity, with two additional microsatellites launched at successive Mars opportunities, and with the first MARSAT launched in 2007. The initial constellation of low-altitude microsatellites will lead to significant increase in the frequency of contact and data return, relative to current Mars Surveyor Program capabilities using direct-to-Earth links and/or polar science orbiters for communciations relay. Data return capability will grow as the constellation grows. Infusion

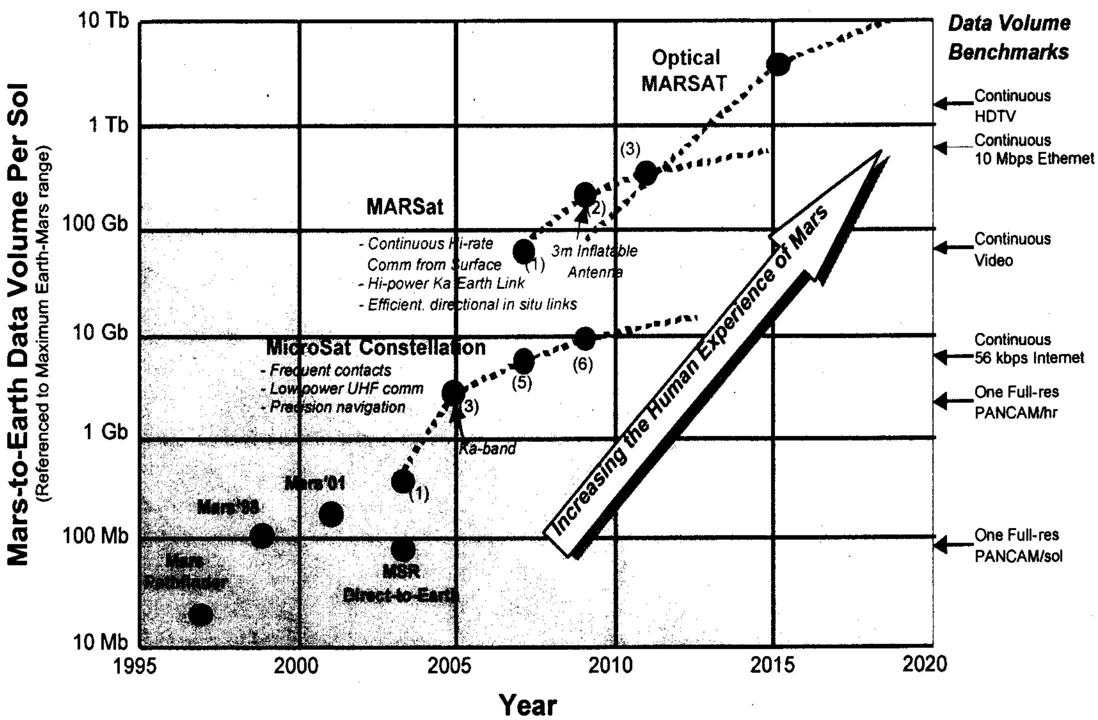

Figure 7: Increase in interplanetary Mars-Earth data return as the Mars Network is deployed

of Ka-band technologies into the microsatellites will further accelerate the growth of bandwidth. The full 6-satellite constellation will be capable of returning on the order of 10 Gb per sol, roughly two orders of magnitude greater than current capabilities, allowing significant growth in data return. This constellation will also support a variety of precision navigation scenarios using Doppler and range observations derived from the UHF communciation links.

The addition of MARSAT leads to another quantum jump in Mars-Earth data bandwidth. The continuous 1 Mb/s data rate translates into a data volume per sol of nearly 100 Gb. With the infusion of inflatable RF spacecraft antennas and, ultimately, laser-based communications for the MARSAT deep space link, even higher data rates can be supported. The orders-of-magnitude growth of Mars data return capability over this time frame will fundamentally change the way both scientists and the public at large experience Mars.

Conclusions

The opportunity exists to start the formation of an Interplanetary Internet in which information flows freely across the solar system to connect scientists and the public to NASA's future space missions. In particular, the intensive exploration of Mars in the coming decade will represent the first instance of this Interplanetary Internet. Communications technology advances that support increased data rates over planetary distances, coupled with efficient short-range communications systems, dedicated relay assets, new IP-like protocols, and methods for efficiently moving information across these deep space links, will greatly increase NASA's capability to deliver on its promise of establishing a virtual presence throughout the solar system.

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